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# FAILURE MODES IN BRITTLE MATRIX COMPOSITES (BMC)

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13. ABSTRACT (Maximum 200 words)

The objective of this program was to derive theoretical models to predict micromechanical fracture events in BMC. Incorporate the micromechanical models into composite laminate theory. Provide experimental confirmation and characterization approaches. Delineate interface/interphase effects on BMC response. This is a bibliography of the publications generated by this program.

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Considerable progress in understanding the behavior of Brittle Matrix Composites (BMC) and the criteria which govern their material design by continuing a systematic study of a class of composites having controlled fiber spacing and both coated and uncoated fibers. Tests on these materials have led to a more satisfying validation of our semi-empirical model of microcrack initiation than we had achieved previously and also a new mechanistic model for this failure mode has been derived. Furthermore, detailed microscopic inspection of failed specimens has displayed numerous features that characterize the failure surfaces and present important challenges for the analyst. In conjunction with our axisymmetric damage model, we are now able to postulate and demonstrate five (including fiber fracture), rather than the commonly assumed two, scenarios of damage initiation and growth. We have also extended the analysis to include secondary cracking, so that damage tolerance issues can be addressed. Models for matrix crack spacing, debond length, fiber penetration, ultimate composite fracture, and very precise details regarding interfacial morphology. Our recently-completed friction and transverse models will provide future support for this study. A monograph has been prepared and is accepted for publication. We have also made significant progress on the derivation and validation of models of the transverse failure modes in both pedigreed and realistic BMCs. Here, the modes of interfacial debonding and radial matrix and coating cracking have been analyzed and compared to experimental observations.

We have initiated the development of the in-house capability to measure thin coating elastic properties by an indentation method, characterization of the interface(s) by application of transverse loading guided by the new model, and inclusion of the effects of friction in the damage analysis. Our future plans call for the application of our micro-mechanical models (and testing) to derive a rigorous failure criterion for structural composites such as graphite-epoxy. Furthermore, it will be necessary to incorporate a micro-continuum model to provide a realistic assessment of the influence of macroscopic stress gradients, which has never been accomplished in the presence of 3D stress concentrations.

We have continued our focus in the environmental initiative on the development of a 3D model, called SVELT to predict accurate stress fields in composite laminates containing cavities, rigid and elastic fasteners, including treatment of surface contact conditions. This model is based on the approximation of stresses by spline functions, which create smooth continuity conditions, unlike the discontinuities that occur in every element of conventional FEM models. Testing has commenced to generate heterogeneous local damage in the layers for comparison with model predictions. We hope to formulate a sound macroscopic criterion for damage initiation at room temperature by coupling this work with the micro-mechanical models. Once this has been accomplished, the effects of elevated temperature and moisture will be studied. Another accomplishment in this area is the development of a laminate model incorporating delamination and transverse cracking failure modes. This model is an important tool in guiding our basic experimental characterization program to measure laminate fracture properties.

Our future plans in this area involve the incorporation of transverse cracks and delamination in the SVELT model and the intensive experimental studies to track damage initiation and growth in a laminate will continue. Correlation of the two are expected to lead to an accurate failure theory at the ply level. This should provide a basic understanding of the so-called bearing failure modes which are handled purely by empirical means in aircraft design at the present time. All this work is the natural precursor to studies under complex environmental conditions.

Attached is a bibliographic listing of publications associated with this work.

## PUBLICATIONS

### Special Journal Publications

1. P. Karpur, T. E. Matikas, and N. J. Pagano, *Fiber-Matrix Interface*, a special issue of Composites Engineering (1995).
2. T. E. Matikas and N. J. Pagano, *Recent Advances in Engineering Science*, a special issue of Composites Part B: Engineering (1998).
3. N. J. Pagano, *Micromechanics of Fiber Reinforced Composites*, a special issue of Composite Science and Technology (1998).

### Technical Papers

72. N. J. Pagano and G. P. Tandon, *Modeling of Imperfect Bonding in Fiber Reinforced Brittle Matrix Composites*, Mech. of Mat., Vol 9 (1990)pp. 49-64.
73. N. J. Pagano and G. P. Tandon, *Thermoelastic Model for Multidirectional Coated-Fiber Composites: Traction Formulation*, Comp. Sci. and Tech., Vol 38 (1990), pp. 247-269.
74. L. R. Dharani, L. Chai and N. J. Pagano, *Steady-State Cracking in Ceramic Matrix Composites*, Comp. Sci. and Tech., Vol. 39 (1990), pp. 29-43.
75. N. J. Pagano and L. R. Dharani, *Micromechanical Models for Brittle Matrix Composites*, in Fiber Reinforced Ceramic Composites, ed. by K. S. Mazdiyasni, Noyes (1990), pp. 40-62.
76. G. P. Tandon and N. J. Pagano, *On the Effective Shear Modulus of Debonding Composites*, Proceedings of the ASC 5th Technical Conference, E. Lansing MI, 12-14 June 1990, pp. 319-325.
77. R. D. Kurtz and N. J. Pagano, *Analysis of the Deformation of a Symmetrically-Loaded Fiber Embedded in a Matrix Material*, Composites Engineering, Vol 1, No 1 (1991).
78. R. Y. Kim and N. J. Pagano, *Crack Initiation in Unidirectional Brittle Matrix Composites*, Journal of American Ceramic Society, v74, n5, May 1991.
79. N. J. Pagano, *Axisymmetric Micromechanical Stress Fields in Composites*, in press.
80. N. J. Pagano and H. W. Brown, III, *The Full-Cell Cracking Mode in Unidirectional Brittle Matrix Composites*, Composites, Vol. 24, No. 2, 1993, pp. 69-83.
81. A. K. Kaw and N. J. Pagano, *Axisymmetric Thermoelastic Response of a Composite Cylinder Containing an Annular Matrix Crack*, Journal of Composite Materials, Vol. 27, No. 6, 1993, pp. 540-571.
82. G. P. Tandon and N. J. Pagano, *Modeling of Interfacial Debonding in Brittle Matrix Composites*, American Society for Composites 7th Technical Conference Proceedings, The Pennsylvania State University, University Park, PA, October 13-15, 1992.
83. N. J. Pagano, *Some Fracture Problems in Unidirectional Brittle Matrix Composites*," Mechanics of Composites Review Proceedings, Dayton, OH, October 27-29, 1992.
84. N. J. Pagano, *Micromechanical Failure Modes in CMC*," AGARD Workshop on Introduction of Ceramics into Aerospace Structural Composites, Antalya, Turkey, April 19, 1993.
85. N. J. Pagano and R. Y. Kim, *Progressive Microcracking in Unidirectional Brittle Matrix Composites*, Proceedings of 1993 Winter Annual Meeting of ASME, New Orleans, LA, November 28, 1993.
86. G. P. Tandon and N. J. Pagano, *Effective Moduli of Unidirectional Fiber Composite Containing Interfacial Arc Microcracks*," Proceedings of 1993 Winter Annual Meeting of ASME, New Orleans, LA, November 28, 1993.
87. G. P. Tandon and N. J. Pagano, *Modeling of Radial Cracking and Interfacial Debonding in Unidirectional Brittle Matrix Composites*, Mechanics of Composites Review Proceedings, Dayton, OH, December 7-8, 1993.
88. R. J. Kerans, T. A. Parthasarathy, P. D. Jero, A. Chatterjee and N. J. Pagano, *Fracture and Sliding in the Fibre/Matrix Interface and Failure Processes in Ceramic Composites*, British Ceramic Transactions, Vol 2, (1993).
89. N. J. Pagano and R. Y. Kim, *Progressive Microcracking in Unidirectional Brittle Matrix Composites*, Mechanics of Composite Materials and Structures, Vol 1, (1994).
90. N. J. Pagano and G. P Tandon, *2-D Damage Model for Unidirectional Composites Under Transverse Tension and/or Shear*, Mechanics of Composite Materials and Structures, Vol 1, (1994).
91. N. J. Pagano and R. Y. Kim, *Progressive Fracture Modes in a Brittle Matrix Composite Under Tension*, Proceedings of the ASME Winter Annual Meeting, Los Angeles, CA (1994).

92. A. K. Kaw, S. Kunchithapatham and N. J. Pagano, *Stress Field in a Cracked Brittle Matrix Composite Cylinder with a Frictional Interface*, Int. J. Solids Structures, Vol 32, (1995).
93. R. Y. Kim and N. J. Pagano, *Progressive Microcracking in a Unidirectional SiC/CAS Composite at Elevated Temperature*, Proceedings of the ASME Winter Annual Meeting, (1995).
94. N. J. Pagano and A. K. Kaw, *Asymptotic Stresses Around a Crack Tip at the Interface Between Planar or Cylindrical Bodies*, Int. J. of Fracture, Vol 71, (1995).
95. N. J. Pagano, *Failure Modes in Brittle Matrix Composites*, COMPOSITES '95: Recent Advances in Japan and the United States, Kokon Shoin, Tokyo, Japan (1995).
96. S. Hu, P. Karpur, T. E. Matikas, L. Shaw and N. J. Pagano, *Free Edge Effect on Residual Stresses and Debond of a Composite Fiber/Matrix Interface*, Mech of Comp Materials and Structures, Vol 2, (1995).
97. R. E. Dutton, N. J. Pagano and R. Y. Kim, *Crack Initiation in Borosilicate Glass-SiC Fiber Composites*, J. Am. Ceramic Soc., Vol 79, (1996).
98. G. P. Tandon and N. J. Pagano, *Matrix Crack Impinging on a Frictional Interface in Unidirectional Brittle Matrix Composites*, Int. J. Solids Structures, Vol 33, (1996).
99. G. P. Tandon and N. J. Pagano, *Effective Thermoelastic Moduli of a Unidirectional Fiber Composite Containing Interfacial Arc Microcracks*, J. Appl. Mechanics, Vol 63, (1996).
100. F. G. Yuan, N. J. Pagano and X. Cai, *Elastic Moduli of Brittle Matrix Composites with Interfacial Debonding*, Int. J. Solids Structures, Vol 34, (1997).
101. S. Hu and N. J. Pagano, *On the Use of a Plane Strain Model to Solve Generalized Plane Strain Problems*, J. Applied Mech., Vol 64, (1997).
102. R. B. Hall and N. J. Pagano, *On the Application of Energy Release Rates*, Composites, Part A: Applied Science and Engineering, Vol 28A, (1997).
103. N. J. Pagano, *On the Micromechanical Failure Modes in a Class of Ideal Brittle Matrix Composites: Part 1: Axial Tension Loading of Coated-Fiber Composites*, to be published in Composites, Part B: Engineering, (1998).
104. N. J. Pagano, *On the Micromechanical Failure Modes in a Class of Ideal Brittle Matrix Composites: Part 2: Axial Tension Loading of Uncoated-Fiber Composites*, to be published in Composites, Part B: Engineering, (1998).
105. G. A. Schoeppner and N. J. Pagano, *Stress Fields and Energy Release Rates in Cross-ply Laminates*, Int. J. Solids, Structures, Vol 35, (1998).
106. G. P. Tandon and N. J. Pagano, *Micromechanical Analysis of Fiber Push-Out and Re-Push Test*, to be published in Composites Science and Technology, (1998).
107. N. J. Pagano, G. A. Schoeppner, R. Y. Kim and F. L. Abrams, *Steady State Cracking and Edge Effects in Thermo-mechanical Transverse Cracking of Cross-Ply Laminates*, to be published in Composites Science and Technology, (1998).

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**PROFESSIONAL PUBLICATIONS**

Abrams, F.L., Pagano, N.J. and Schoeppner, G.A.,"Edge Effects in Thermal Cracking of Composites for Space Applications," to be presented at the 1997 Joint ASME/ASCE/SES Summer Meeting, Northwestern University, Evanston, IL, June 29 - July 2, 1997

Kim, R.Y., Schoeppner, G.A. and Crasto, A.S.,"Measured and Predicted Changes in Laminate CTE Due to Microcracking," Proceedings of the American Society for Composites, Dearborn, MI, October 6-8, 1997, pp. 1103-1112

Pagano, N.J. and Schoeppner, G.A.,"Some Transverse Cracking Problems in Cross-ply Laminates," proceedings of the 38th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 7-10, 1997, Kissimmee, FL

* Pagano, N.J., Schoeppner, G.A., Kim, R. and Abrams, F.L.,"Steady State Cracking and Edge Effects in Thermo-mechanical Transverse Cracking of Cross-ply Laminates," accepted for publication in Composites Science and Technology, 1998

Schoeppner, G.A. and Pagano, N.J., 'Modelling Cracked Flat Laminates using an Axisymmetric Formulation,' Proceedings of the ICCE/2 Conference, August 21-24, 1995, New Orleans, LA

* Schoeppner, G.A. and Pagano, N.J.,"Stress Fields and Energy Release Rates in Cross-ply Laminates, " International Journal of Solids and Structures, Vol. 35, No. 11, 1998, pp. 1025-1055

Tandon, G.P. and Schoeppner, G.A.,"Axisymmetric Damage Model (ADM), User's Manual" - 4/96

## Peer Reviewed Archival Journal Articles

1. R. B. Hall and N. J. Pagano, "On the Application of Energy Release Rates," *Composites, Part A: Applied Science and Manufacturing,* vol. 28A (1997), 833-838.
2. R. B. Hall, "Matrix-Dominated Viscoplasticity Theory for Fibrous Metal Matrix Composites, *Composites, Part A: Applied Science and Manufacturing,* vol. 28A (1997), 769-780.
3. Richard B. Hall and Joseph W. Hager, "Performance Limits for Stiffness-Critical Graphitic Foam Structures, Part I: Comparisons with High-Modulus Foams, Refractory Alloys and Graphite-Epoxy Composites," *Journal of Composite Materials*, Vol. 30, no. 17 (1996), 1922-1937.
4. Richard B. Hall, "Performance Limits for Stiffness-Critical Graphitic Foam Structures, Part II: Comparisons of Foams, Foam-Core and Honeycomb-Core Sandwiches in Bending/Shear," *Journal of Composite Materials*, Vol. 30, no. 17 (1996), 1938-1956.
5. Hall, R., "Effective Moduli of Cellular Materials," J. Reinforced Plastics and Composites, vol. 12, no. 2, Technomic, (1993), 186-197.

## Peer Reviewed Proceedings (non-invited)

1. R. B. Hall and J. W. Hager, "Evaluation of Graphitic Foams as Low Mass Structural Materials," in *Novel Forms of Carbon II,* MRS Symposium Proceedings Series Vol. 349, C. L. Renschler, D. M. Cox, J. J. Pouch, Y. Achiba, eds., Materials Research Society, Pittsburgh, 1994.
2. S.L. Gunderson and R.B. Hall, "Preformed Holes for Improved Mechanical Properties of Laminated Composites with Unidirectional Plies," Advanced Materials: Performance Through Technology Insertion, Science of Advanced Materials and Process Engineering Series Vol. 38, Book 1, Bailey, V., Janicki, G. C. and Haulik, T., eds., Society for the Advancement of Material and Process Engineering, Covina, CA, pp. 81-91, June 1993.
3. Hall, R., "Matrix-Dominated Thermoviscoplasticity in Fibrous Metal-Matrix Composite Materials," in Singhal, S. N., Jones, W. F. and Herakovich, C. T. (eds.),*Mechanics of Composites at Elevated and Cryogenic Temperatures,* AMD-Vol. 118, ASME, New York, pp. 39-54, Dec 1991.

## Invited Papers

### a. Peer Reviewed Proceedings

1. Hall, R., "Viscoplasticity Theory for Matrix-Dominated Deformation of Metal Matrix Composites," in Haritos, G. K., Ochoa, O. O. (eds.), Damage and Oxidation

Protection in High Temperature Composites, Vol. 2, AD-Vol. 25-2, ASME, New York, 1992.

**b. Non Peer Reviewed (no proceedings)**

1. R. Hall, "Structural Biomimetics: Natural Features for Advanced Materials," Mechanics and Materials for Next Generation Armor, Army Research Office, Durham NC, 26-27 Jan 94.
2. R. Hall, "Biotechnology for Advanced Structural Materials," AFOSR Biomimetics Workshop, Wright-Patterson AFB, OH (August 1993).

**Non Peer Reviewed Proceedings (non-invited)**

1. R. B. Hall and N. J. Pagano, "Strain Energy Release Rate Application Limits and Errors," Proceedings of ICCE/3, New Orleans LA, 21-26 Jul 96.
2. R. B. Hall, "Performance Limits for Graphitic Foams Compared to Available Advanced Materials in Stiffness-Critical Structures," Proceedings of ICCE/2, New Orleans, LA, 21-24 Aug 95.
3. R. Hall and J. W. Hager, "Graphitic Foams for Low-Mass Structures," 18th Annual Mechanics of Composites Review, Dayton OH, December 1993.
4. E. V. Iarve, R. Hall, K. E. G. Thorp and S. L. Gunderson, "Stress Analysis of Laminated Composites with Preformed Holes," Proceedings of the American Society for Composites 8th Technical Conference on Composite Materials, Cleveland OH (October 1993)
5. R. Hall and J. W. Hager, "Graphitic Foams as Potential Structural Materials," Proceedings of the 21st Biennial Conference on Carbon, Buffalo, NY (June 1993).
6. Hall, R., "Effective Moduli of Cellular Materials," Proceedings of the American Society for Composites, 6th Technical Conference, Albany NY, October 1991, Technomic, pp.1080-1089.
7. Hall, R., "Bimodal Viscoplasticity in Fibrous Metal-Matrix Composite Materials," in *Symposium on High Temperature Composites,* Pagano, N. J. and Soni, S. R., eds., Technomic, 1989, pp. 21-30.

**PhD Thesis**

Hall, R., "Matrix-Dominated Thermoviscoplasticity in Fibrous Metal-Matrix Composite Materials," Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, Rensselaer Polytechnic Institute, 1990.

## Nonpublished, Non-Invited Conference Presentations

1. Hall, R., "Mechanical Modeling of Structural Foams," March 26, 1992, at AIAA Minisymposium, Dayton Holiday Inn.
2. Hall, R., "Matrix-Dominated Thermoviscoplasticity in Fibrous Metal-Matrix Composite Materials," March 14, 1991, at AIAA Minisymposium, Dayton Holiday Inn.

## ML Seminar and Award Presentations (WUD45 presentations omitted)

1. Hall, R. B. and Pagano, N. J., : "On the Application of Energy Release Rates," Cleary Award presentation, March 1997.
2. Hall, R. B., "Performance Limits for Stiffness-Critical Graphitic Foams, Composites and Structures" Cleary Award presentation, March 1996.
3. Hall, R., "Matrix-Dominated Viscoplasticity Theory for Fibrous Metal-Matrix Composites," Cleary Award presentation, March 1992.
4. Hall, R., "Thermoviscoplasticity in Fibrous Metal-Matrix Composite Materials," June 13, 1991, in-house to NIC/ML high-temperature composites group.